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Amorphous water ice within icy planetesimals survives collisional evolution in the early Solar System

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Abstract

We explore the effects of collisional evolution on the composition of planetesimals during dynamical instabilities in the early Solar System. Specifically, how the resulting shock heating crystallizes Amorphous Water Ice (AWI). We find that such collisions crystallize only a small fraction of the AWI present in a typical icy planetesimal, leaving the majority (>85%) of the ice in the amorphous state. Furthermore, small impacts crystallize a mantle of water ice on the object's surface, but do not affect the underlying AWI.

1. Introduction

Amorphous water ice (AWI) is a solid phase of water ice lacking a crystalline structure, forming a glass [1]. Conditions in the Sun's proto-planetary disk favour AWI formation [2,3], which. later adsorbed onto silicate grain surfaces as complete icy grains or included in into mixed silicate grains, and then accreted together to form the original population of cometary bodies in the outer solar system [4]. Following formation, dynamical instabilities (e.g., Nice Model) triggered massive dynamical evolution that scattered these icy planetesimals into the Oort Cloud and Scattered Disk, the two reservoirs of comets in our solar system [5,6]. This dynamical excitation caused collisional evolution of the icy planetesimal population [7]. Hypervelocity impacts can produce significant shock heating, which changes the temperature-dependent crystallization rate of AWI [8], reducing the amount of AWI present in the icy planetesimal.

Understanding the survival/destruction of AWI is important to understanding the mechanisms driving cometary activity. AWI can trap supervolatile species during its formation, and later release them upon crystallization [9]. Thus, if AWI is present in comets, its crystallization may contribute to supervolatile production rates [10]. Nevertheless, AWI has never been conclusively detected on an icy body's surface in the present Solar System [11], although two tentative, weak spectroscopic detections of AWI have been reported [12,13]. This begs the question: can amorphous water ice even survive collisional evolution in the early Solar System?

2. Methods

We use the iSALE impact shock physics hydrocode to simulate impacts between icy planetesimals. iSALE expands upon the SALE shock-physics hydrocode [14] to include an elastic-plastic constitutive model for impacts into solid bodies, material fragmentation models, multiple materials and their equations of state [15,16], and modified strength models [17]. More recently, the creation of porosity through dilatancy [18] and porous compaction of materials [19,20] have been incorporated into iSALE. We simulate both collisions between 100 km primordial [21] AWI planetesimals, and small (1 km) AWI impactors striking 100 km AWI planetesimals. Impact velocities are between 2-4 km/s (the expected range following Nice-style instabilities) [7]. Both bodies have a uniform initial temperature of 100 K (neglecting any substantial thermal evolution preceding the collision event).

iSALE does not have an equation of state for amorphous water ice. Although the crystallization of pure AWI is highly exothermic, impure AWI with ~2% CO or CO_2 impurities releases no heat, and higher concentrations of impurities render AWI crystallization endothermic [22]. Thus, typical CO_2 abundances (~2-10% relative to water) [23] alone are sufficient to render AWI crystallization non-exothermic. Other similar physical properties between AWI and amorphous water ice (e.g., similar densities of 940 kg/m^3 and 920 kg/m^3, respectively) allow the crystalline water ice equation of state to substitute for AWI, to allow for reasonably accurate computation of the shock pressures, temperatures, and crater morphology. We use tracers in iSALE to track the pressures and temperatures experienced by material throughout the bodies during the impact process.

We feed the iSALE tracer information into a script that computes the crystallized fraction of water ice over time. We modify the Gibbs Free Energy approach of Kouchi et al. [8] to compute the amount of AWI crystallized ($\Delta\theta$) over time step Δt:

$$\Delta\theta = (1-\theta)4\left(\frac{\Delta t}{\tau}\right)^4 e^{\left(\frac{\Delta t}{\tau}\right)^4} \quad (1)$$

$$\tau = \left(\frac{1}{2\pi\alpha}\right)^{\frac{1}{4}}\left(\frac{\mathrm{kT}}{\sigma}\right)^{\frac{1}{8}}\frac{\Omega^{\frac{2}{3}}}{\mathrm{D_0}}\,\mathrm{e}^{\frac{1}{\mathrm{kT}}\left[\mathrm{E}\alpha+\frac{4\pi\sigma^3}{3\mathrm{L}^2}\left(\frac{\mathrm{T_m}}{\mathrm{T_m}-\mathrm{T}}\right)^2\right]} \quad (2)$$

where τ is the crystallization timescale, α is a geometrical factor that depends on the morphology of crystal growth, Ω is the effective volume of a water molecule, $\sigma = \gamma\Omega^{2/3}$ where γ is the interfacial tension (i.e., surface tension), $\mathrm{D_0}$ is an empirical reference diffusion constant, $\mathrm{E_\alpha}$ is the activation energy of self-diffusion, L is the enthalpy of crystallization per molecule at 0 K, and $\mathrm{T_m}$ is the freezing point temperature, where solid and liquid co-exist [8].

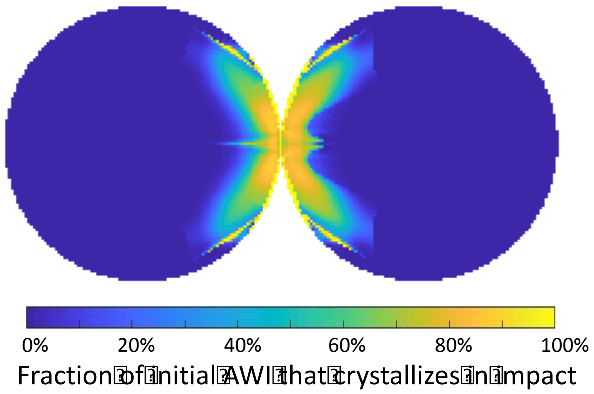

Figure 1: The fraction of AWI that crystallizes during a catastrophic collision between two 100 km AWI planetesimals. The collision fully disrupts the planetesimals, thus the AWI that crystallizes is traced back to its initial position within the planetesimals.

3. Results and Conclusions

We find that such collisions between 100 km planetesimals lead to significant crystallization of AWI near the impact site (fig. 1), and completely disrupt both planetesimals. Nevertheless, 85% of the planetesimals' volume experiences little crystallization of its AWI (<10% crystallization). Thus, the disrupted planetesimals would reaccrete into objects that are relatively AWI-rich. Even with multiple catastrophic collisions, significant amounts of AWI would survive this collisional evolution.

Small impacts (1 km impactors) also crystallize AWI near the impact site, with little AWI crystallization occurring below the transient crater. Because small impactors numerically dominate the impactor flux, impact gardening will crystallize the surface regolith, leaving abundant AWI present below the regolith layer, consistent with previous micrometeorite bombardment studies [24]. Thus, if AWI were present in icy planetesimals, it is unlikely to be detected due to the crystalline water mantle that coats the surface of the body, consistent with observations [11].

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